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EFFECT OF MOISTURE ON THE COMPRESSIVE STRENGTH OF PLYWOOD AND LAMINATED WOOD

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EFFECT OF MOISTURE ON THE COMPRESSIVE STRENGTH OF PLYWOOD AND LAMINATED WOOD[1]

By

JOHN T. DROW, Associate Engineer
and
J. A. LISKA, Assistant Engineer

The strength properties of wood are known to be influenced by its moisture content. Frequently it is not feasible to condition specimens or structures to the same or to a standard moisture content at the time of test. Consequently, a means of adjusting test results for the effect of varying moisture contents on strength properties is necessary to attain comparability among the tests of a series or to other similar data.

A method of adjusting test data on the strength properties of wood at different moisture contents has been developed and published by the Forest Products Laboratory.[2] There has, however, been no specific information dealing with moisture content-strength relations for such wood assemblies as plywood or laminated construction. Adjustments of results from tests of these forms have been possible only by assuming that the adjustments for solid wood members apply. To determine the validity of this assumption, compression tests were made at the Forest Products Laboratory on plywood and laminated wood specimens of Douglas-fir and Sitka spruce.

Material

Rotary cut veneer of several thicknesses was produced from four specially selected logs, two of Douglas-fir (coast type) and two of Sitka spruce, at Tacoma, Wash., dried and shipped to Madison, Wis., where it was glued up at the Laboratory with casein glue into plywood and laminated wood of various numbers of plies. Veneer sheets placed in corresponding locations in the plywood and laminated wood assemblies were taken from adjacent

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[1] This mimeograph is one of a series of progress reports issued by the Forest Products Laboratory to aid the Nation's war program. Results here reported are preliminary and may be revised as additional data become available. The work here reported was done in cooperation with the Aeronautical Board.

[2] U. S. Dept. Agr. Tech. Bul. 282; U. S. Dept. Agr. Tech. Bul. 479; U. S. Dept. Agr. Unno. Pub., "Wood Handbook;" Forest Products Lab. Mimeo. 1313; and ANC Handbook on the Design of Wood Aircraft Structures (Restricted).

positions in larger sheets of veneer in order to make the two kinds of assemblies as nearly alike in material as possible.

The specimens for these tests were cut from plywood and laminated beams made up from the material described and used in a previous series of tests. The specimens were side or end matched to provide, insofar as possible, similar specimens for each moisture condition.

In each laminated specimen the grain of all plies was either parallel or perpendicular to the long axis. In each plywood specimen, the grain of the face plies was either parallel or perpendicular to the long axis.

Three types of plywood specimens were used: 9-ply, of 1/16-inch veneer, with a nominal thickness of 9/16 inch; 5-ply, of 3/16-inch veneer, with a nominal thickness of 15/16 inch; and 7-ply, of 3/16-inch veneer, with a nominal thickness of 1-5/16 inches. The 5- and 7-ply specimens were 4 inches long, the 9-ply specimens 3-1/2 inches long.

Conditioning

The veneer had been dried to an unknown moisture content at the producing plant, when manufactured, and was reconditioned to approximately 10 percent moisture content at the Laboratory before being glued up. The gluing operation added moisture so that, after gluing, it was necessary to condition the plywood and laminated wood beams to approximately 10 percent moisture content. After these beams were tested they were stored for about 4 years in a room exposed to fluctuating atmospheric humidity and, occasionally, heated artificially. When the beams were cut into specimens for the tests herein reported, their moisture content averaged about 6 percent.

The 9-ply specimens were subjected to either 76° F. and 65 percent relative humidity or 80° F. and 90 percent relative humidity. The 5-ply and 7-ply specimens were subjected to one of the above conditions or to either 80° F. and 30 percent relative humidity or 80° F. and 80 percent relative humidity. Conditioning was continued until the specimens appeared to have reached constant weight.

The equilibrium moisture content attained by the specimens appeared to be somewhat lower, in general, than would be expected in the case of solid wood subjected to the same conditioning processes (table 1).

Table 1.--Average moisture content of test specimens after storage to constant weight in various conditions of temperature and relative humidity

Material	Moisture content after conditioning at --			
	80° F. and 30 percent relative humidity	76° F. and 65 percent relative humidity	80° F. and 80 percent relative humidity	80° F. and 90 percent relative humidity
	Percent	Percent	Percent	Percent
Solid wood (average equilibrium moisture content)	6	12	17	22
Douglas-fir				
5- and 7-ply, 3/16-inch veneer	5.8	8.6	12.7	16.6
9-ply, 1/16-inch veneer	--	9.6	--	19.0
Sitka spruce				
5- and 7-ply, 3/16-inch veneer	6.2	10.0	14.2	18.4
9 ply, 1/16-inch veneer	--	10.3	--	20.8

Testing Procedure

A total of 640 specimens, four for each variable were tested. Half were of laminated and half of plywood construction. All were tested in compression, with the direction of the applied load parallel to the long dimension of the specimen as indicated in figure 1.

Properties Investigated

Data were obtained for determinations of moisture content, specific gravity, fiber stress at proportional limit, maximum crushing strength, and modulus of elasticity. No correction was applied to strength values for differences in specific gravity, as specimens from each log varied but slightly in this respect. Formulas used in computing these properties were:

Moisture content (percent):

$$M = \frac{\text{Weight at time of test - oven-dry weight x 100}}{\text{oven-dry weight}}$$

Specific gravity:

$$G = \frac{\text{Weight in grams at time of test - estimated weight of glue}}{\left(1 + \frac{\text{percent moisture}}{100}\right) \times \text{volume in cubic centimeters at time of test}}$$

Fiber stress at proportional limit:

$$S_{PL} = \frac{\text{Load at proportional limit in pounds}}{\text{Cross-sectional area of specimen in square inches}}$$

Maximum crushing strength:

$$S_c = \frac{\text{Maximum load in pounds}}{\text{Cross-sectional area of specimen in square inches}}$$

Modulus of elasticity:

$$E_c = \frac{\text{Load in pounds x gage length in inches}}{\text{Cross-sectional area in square inches x deformation in inches between gage points corresponding to above load}}$$

Analysis of Results

The formula derived in previous Forest Products Laboratory research[2] to represent the relation between strength values and moisture content for solid wood is

$$S = S_o \times 10^{-KM}$$

in which S is the strength value at moisture content M, S_o is the strength value that would obtain at zero moisture content if the equation were valid to that point, and K is a constant or parameter to adapt the equation to a particular set of data. Values computed from this formula are on a straight line when strength values are plotted to a logarithmic scale as ordinates and the corresponding values of moisture content to an arithmetic scale as abscissas. The slope of this line with respect to the axis of abscissas is -K.

To investigate the applicability to plywood and laminated wood of the methods of adjustment that have been derived for solid wood, it was necessary to determine: (1) whether the data from tests of plywood and laminated wood conform to a straight-line relationship when plotted as described above, and (2), whether the slopes of such lines are the same as those of curves found for solid wood.

In making these determinations, individual graphs were drawn for specimens from each log, for each of the two types of construction, and for each of the three strength properties under consideration. Figure 2 gives examples of these graphs.

Conformity to Linear Relationship

As previously indicated, tests of the 9-ply constructions were made on specimens at but two values of moisture content. Hence, they afford no data for study of conformity to a linear relationship.

The graphs representing the 5-ply and 7-ply specimens, on which tests were made at four differing moisture content values, indicated a linear relationship between moisture content and strength. In many of the graphs, the four points were almost perfectly on a straight line. In other cases, three points were practically on a straight line, with the fourth point falling to one side or the other. In a number of instances, however, a straight-line relationship was not apparent.

The degree of agreement found between plotted points as to their straight-line relationship was considered as satisfactory as could be expected from the limited number of tests considered. It was, therefore, concluded that the strength-moisture relationship for plywood and laminated wood can be represented by the formula derived for solid wood.

Comparison of Value of K for Plywood and Laminated Wood with Corresponding Values for Solid Wood

The general equation of a straight line on the graphs representing the data of this test is

$$\text{Log } S = \log S_o - KM$$

which is equivalent to

$$S = S_o \times 10^{-KM}$$

the equation previously presented. The parameter K, as previously indicated, is numerically equal to the slope but of opposite algebraic sign. Thus, K is positive and the slope negative for those properties that increase with decrease in moisture content, which includes all properties investigated in this series of tests.

The parameter K may also be expressed in terms of the percentage change in strength properties for a 1 percent change in moisture content. The figures given in table 2-2 of the ANC Handbook on the Design of Wood Aircraft Structures (1942) are such average percentage correction factors for solid wood. As shown in the Appendix, these percentage corrections and the values of K are readily convertible.

Table 2 presents the average values of percentage change as found from the tests of plywood and laminated wood, and for comparison certain values from U. S. Dept. Agr. Tech. Bul. 282 and from Table 2-2 of the ANC Handbook. Lines with the slopes represented by these comparison values are also shown in figure 2.

It is to be expected that the effects of moisture content on maximum crushing strength and on fiber stress at proportional limit in compression parallel to the grain will be the same for laminated as for solid wood. Furthermore, since resistance to compression is, in plywood, contributed principally by the plies that are parallel to the direction of load, it is

to be expected that moisture effects on plywood will be the same as for solid wood whether the loading is parallel or perpendicular to the face plies. These expectations with respect to maximum crushing strength are in general confirmed by the comparisons in columns 3 to 9 of table 2, although it may be noted that the values for plywood and laminated construction tend to be slightly higher than those for solid wood.

The data of table 2 (columns 7 to 12) indicate also that the fiber stress at proportional limit and maximum crushing strength differ but little with respect to the effects of moisture content. This is in agreement with data for softwood species given in table 16 of U. S. Dept. Agr. Tech. Bul. 479 where the ratios of strength at 12 percent moisture to strength in the green condition are given as 1.86 for fiber stress at proportional limit and 1.97 for maximum crushing strength.

For perpendicular-to-grain tests on laminated wood, the values in columns 10 to 12 of table 2 are not directly comparable to those in columns 4 to 6 because of the difference in areas loaded in test (see footnote 4, table 2). Values in columns 7 to 9 refer furthermore to maximum crushing strength, whereas those in columns 4 to 6 relate to proportional limit values. It may be noted that values in columns 10 to 12 are, in general, slightly higher than those in columns 7 to 9, which suggests that for this kind of test fiber stress at proportional limit may be influenced more by moisture content than is maximum crushing strength.

Values in columns 16 to 18 for plywood and for laminated wood loaded parallel to the grain when compared to values in columns 13 to 15 indicate that the effect of moisture on modulus of elasticity in compression parallel to grain is slightly greater than on modulus of elasticity in bending. On the other hand, the values for laminated wood tested perpendicular to the grain show that the effect of moisture is much greater on modulus of elasticity in compression perpendicular to grain than on modulus of elasticity in bending.

Other Relationships

Agreement to a straight-line relationship between moisture content and strength is, in general, somewhat better for plywood than for laminated wood. The variation of points for the laminated construction is greater for specimens tested perpendicular to the grain than for those tested parallel to the grain. There seems also to be a greater variation for plywood tested with outer plies perpendicular to the direction of load than for the opposite construction. The various points representing fiber stress at proportional limit are more erratic than those for maximum crushing strength, and the points for modulus of elasticity are still more erratic.

The slope appears to be independent of the number of plies in the laminated wood, and no consistent variation is apparent in the plywood.

Conclusions

The conclusions from this study, based on compression tests of Douglas-fir and Sitka spruce, are:

1. The type of moisture adjustment formula that has been found suitable for wood is applicable to plywood and laminated construction.

2. The parameter that adapts the type formula to a specific property and species is variable for either solid wood or the other forms, but the values found in this series of tests are for the most part within the same range as that previously found for solid wood.

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APPENDIX

Derivation of Correction Factors of Table 2-2 in the ANC Handbook on the Design of Wood Aircraft Structures (1942)

The fundamental equation representing the relationship between moisture content and strength of wood is

$$S = S_o \times 10^{-KM}$$

Let S_1 = strength value at moisture content M_1

S_2 = strength value corrected to moisture content M_2

Then
$$S_1 = S_o \times 10^{-KM_1} \qquad (1)$$

and
$$S_2 = S_o \times 10^{-KM_2} \qquad (2)$$

If the moisture content changes from M_1 to M_2, there will be a change in the strength property. The ratio of the new strength value S_2 to the original value S_1 is found by dividing equation (2) by equation (1)

$$\frac{S_2}{S_1} = \frac{S_o \times 10^{-KM_2}}{S_o \times 10^{-KM_1}} = \frac{10^{-KM_2}}{10^{-KM_1}} = 10^{K(M_1 - M_2)}$$

or
$$S_2 = S_1 \times 10^{K(M_1 - M_2)}$$

or
$$S_2 = S_1 \, (10^{K})^{M_1 - M_2} \qquad (3)$$

P, the change in strength, expressed as a ratio to the original strength, is then:

$$P = \frac{S_2 - S_1}{S_1} = \frac{S_2}{S_1} - 1 = (10^K)^{M_1 - M_2} - 1$$

When $M_1 - M_2 = 1$, this becomes

$$\frac{S_2 - S_1}{S_1} = 10^K - 1 = P_{-1}$$

where P_{-1} is the percentage change (expressed decimally) in strength for a decrease of 1 percent in moisture content.

whence $$10^K = 1 + P_{-1} \qquad (4)$$

Combining equations (3) and (4)

$$S_2 = S_1 (1 + P_{-1})^{M_1 - M_2} \qquad (5)$$

Values of P_{-1} are given in table 2-2 of the ANC Handbook on the Design of Wood Aircraft Structures, that is, the values of table 2-2 are the percentage changes in strength value that accompany a decrease of 1 percent in moisture content. (The parentheses in the title of table 2-2 are erroneous.)

In the use of equation (5) it is necessary to observe the algebraic sign of P_{-1} as given in table 2-2. It may noted that when correction is to be made to a lower moisture content, $M_1 - M_2$ is positive and the original strength is multiplied by a power of $(1 + P_{-1})$; and when correction is to a higher moisture, $M_1 - M_2$ is negative and the original strength is divided by a power of $(1 + P_{-1})$.

Table 2.--Percentage increase in strength corresponding to a decrease of 1 percent in moisture content. Values for plywood and laminated wood compared to values for solid wood.

Direction of face and alternate plies with respect to direction of load	Species	Log number[1]	Maximum crushing strength: Values from -- Tech. Bul.[2] No. 282 Table 24	Maximum crushing strength: Values from -- ANC[3] Table 2-2	Maximum crushing strength: Values from present tests 5-ply	Maximum crushing strength: Values from present tests 7-ply	Maximum crushing strength: Values from present tests 9-ply	Fiber stress at proportional limit: Values from present tests 5-ply	Fiber stress at proportional limit: Values from present tests 7-ply	Fiber stress at proportional limit: Values from present tests 9-ply	Modulus of elasticity: In bending values from -- Tech. Bul.[2] No. 282 Table 24	Modulus of elasticity: In bending values from -- ANC[3] Table 2-2	Modulus of elasticity: In compression values from present tests 5-ply	Modulus of elasticity: In compression values from present tests 7-ply	Modulus of elasticity: In compression values from present tests 9-ply
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
			Solid wood			Laminated wood						Solid wood			Laminated wood		
			Min.	Max.								Min.	Max.				
Parallel	Douglas-fir	1	3.2	6.7	5.5	5.5	6.5	6.0	4.7	5.5	6.0	1.0	2.6	1.8	3.5	3.0	2.7
	"	2	3.2	6.7	5.5	5.2	6.0	6.0	5.0	3.5	6.5	1.0	2.6	1.8	1.8	1.8	1.8
	Sitka spruce	1	4.5	6.1	5.3	6.5	6.9	6.3	6.0	7.0	9.0	1.2	3.0	1.7	-	2.5	1.7
	"	2	4.5	6.1	5.3	6.5	6.7	6.6	7.0	8.0	7.5	1.2	3.0	1.7	-	1.7	1.7
Perpendicular	Douglas-fir	1	±1.2	±9.2	±5.0	5.4	6.0	6.5	8.5	7.0	9.4	1.0	2.6	1.8	5.0	3.9	8.0
	"	2	±1.2	±9.2	±5.0	5.0	5.0	5.0	5.0	8.0	9.0	1.0	2.6	1.8	6.0	5.8	7.5
	Sitka spruce	1	±2.9	±7.6	±4.3	9.5	7.0	8.0	-	9.0	6.5	1.2	3.0	1.7	-	7.0	9.5
	"	2	±2.9	±7.6	±4.3	6.5	6.8	7.5	8.0	8.0	9.0	1.2	3.0	1.7	7.0	8.7	6.0
			Plywood												Plywood		
Parallel	Douglas-fir	1	3.2	6.7	5.5	5.5	5.5	5.0	3.5	5.3	5.0	1.0	2.6	1.8	2.5	1.8	1.8
	"	2	3.2	6.7	5.5	5.7	6.5	5.5	4.0	4.0	5.5	1.0	2.6	1.8	1.8	1.5	1.5
	Sitka spruce	1	4.5	6.1	5.3	5.5	6.5	5.5	6.0	7.5	7.0	1.2	3.0	1.7	3.0	1.7	1.0
	"	2	4.5	6.1	5.3	6.0	6.5	6.0	5.0	8.0	6.5	1.2	3.0	1.7	1.7	.7	2.0
Perpendicular	Douglas-fir	1	3.2	6.7	5.5	5.5	5.4	6.5	4.5	5.8	5.5	1.0	2.6	1.8	3.0	3.5	2.5
	"	2	3.2	6.7	5.5	5.5	5.5	6.2	4.0	4.2	6.0	1.0	2.6	1.8	2.4	2.8	2.5
	Sitka spruce	1	4.5	6.1	5.3	7.0	6.5	6.5	6.9	7.1	7.5	1.2	3.0	1.7	1.6	1.3	2.1
	"	2	4.5	6.1	5.3	6.5	6.5	6.5	7.0	8.0	6.5	1.2	3.0	1.7	1.5	2.0	2.0

[1] These numbers do not apply to columns 4, 5, 6, 13, 14, or 15.

[2] U. S. Dept. Agr. Tech. Bul. 282, "Strength-moisture Relations for Wood," 1932

[3] ANC Handbook on the Design of Wood Aircraft Structures (Restricted), 1942.

[4] These values apply to fiber stress at proportional limit in the standard compression-perpendicular-to-grain test, in which load is applied to only part of the area of the specimen. Other values on the same lines, except in columns 13 to 15, are for laminated specimens loaded perpendicular to the grain over the full area (see figure 1).

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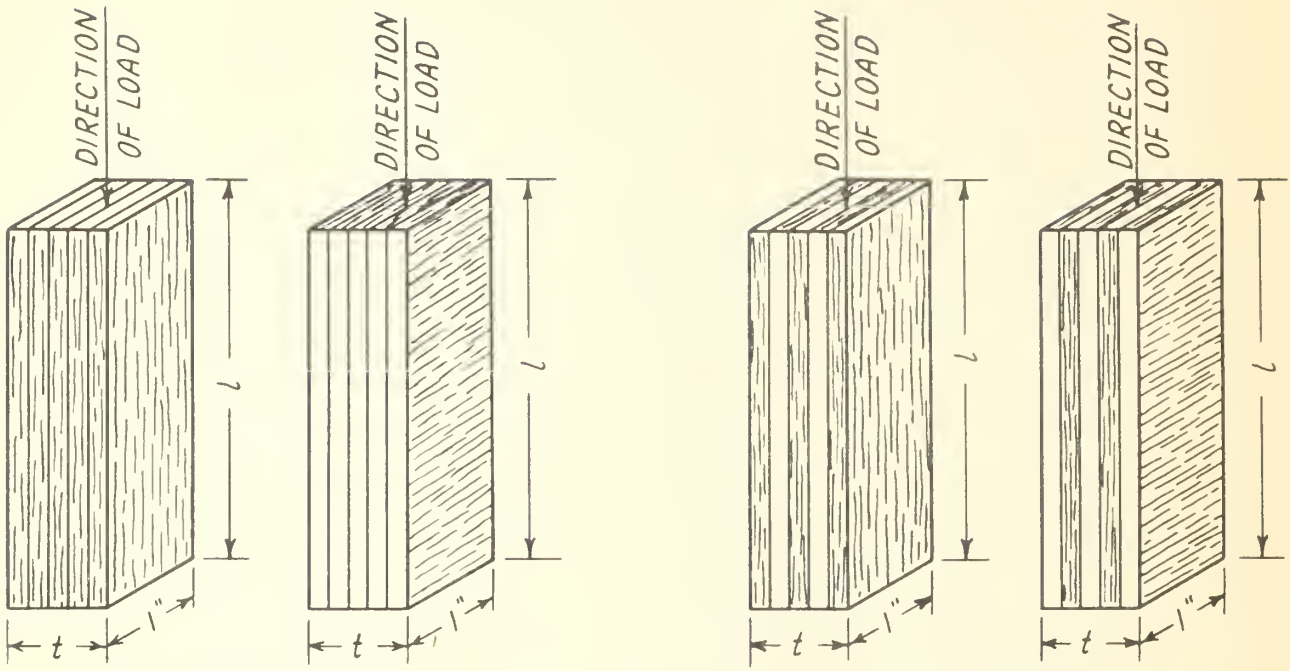

LAMINATED WOOD

GRAIN OF ALL PLIES PARALLEL TO DIRECTION OF LOAD

GRAIN OF ALL PLIES PERPENDICULAR TO DIRECTION OF LOAD

PLYWOOD

GRAIN OF FACE AND ALTERNATE PLIES PARALLEL TO DIRECTION OF LOAD.

GRAIN OF FACE AND ALTERNATE PLIES PERPENDICULAR TO DIRECTION OF LOAD

LEGEND

5-PLY : $t = \frac{15}{16}$", $l = 4$"

7-PLY : $t = 1\frac{5}{16}$", $l = 4$"

9-PLY : $t = \frac{9}{16}$, $l = 3\frac{1}{2}$"

FIG. 1

CONSTRUCTION OF SPECIMENS USED TO TEST MOISTURE CONTENT-STRENGTH RELATIONS IN PLYWOOD AND LAMINATED WOOD IN COMPRESSION

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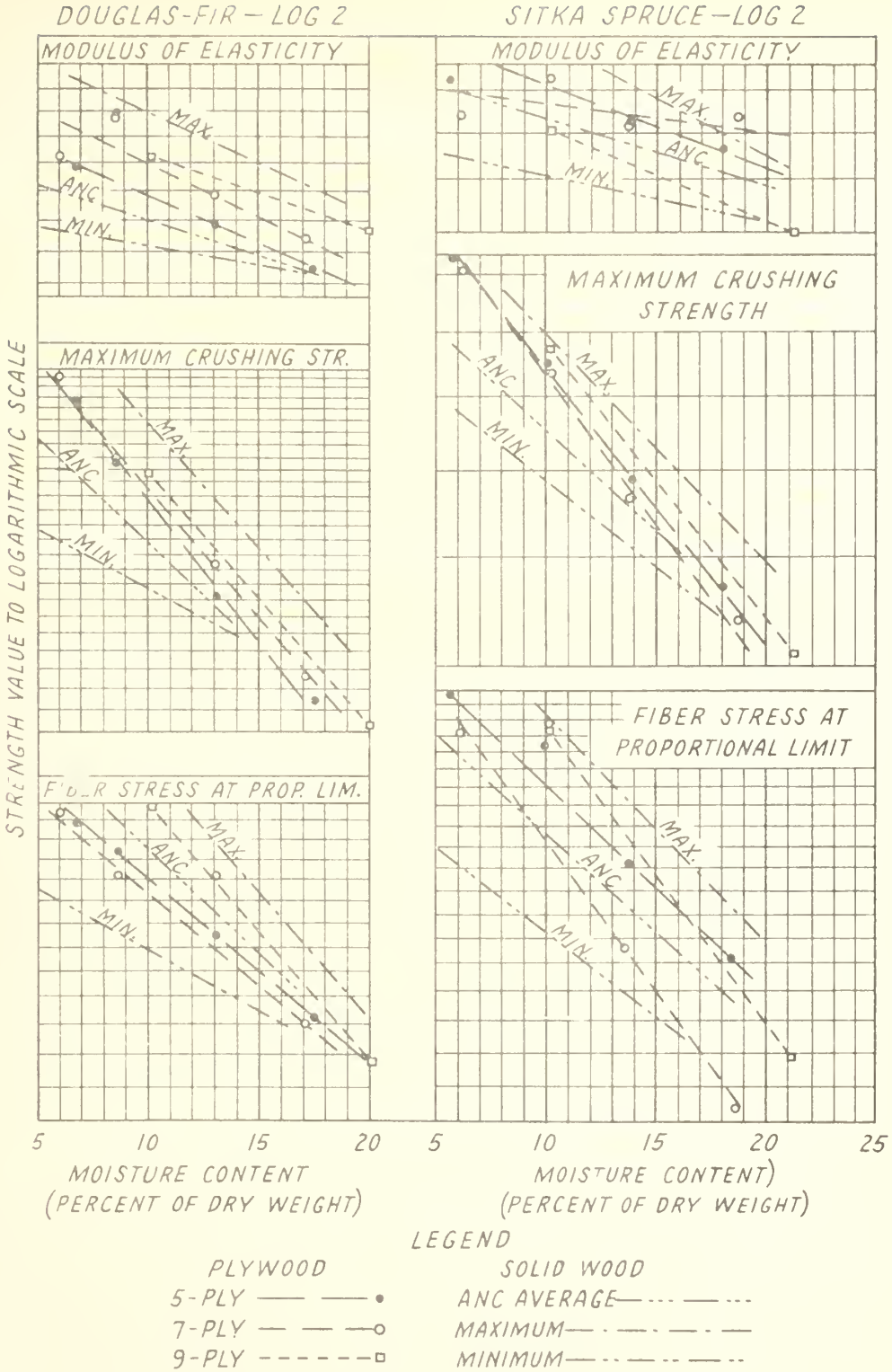

FIG. 2
RELATION OF VARIOUS STRENGTH PROPERTIES
TO MOISTURE CONTENT IN PLYWOOD
WITH GRAIN OF FACE PLIES PARALLEL TO DIRECTION OF LOAD

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SUMMARY

This report presents the results of compression tests of Douglas-fir and Sitka spruce plywood and laminated wood specimens of several constructions at a number of moisture content values. Comparison of the strength-moisture relationship of these materials with that for solid wood shows that the type of moisture adjustment formula that has been found suitable for wood is applicable to plywood and laminated construction as well. Such comparison also shows that the parameter used to adapt the general formula to a particular property and species is variable for plywood and laminated construction as well as for solid wood, but that the values found in this series of tests are for the most part within the same range as previously found for solid wood.

These conclusions are, of course, based only on the results of compression tests on Douglas-fir and Sitka spruce, but probably apply to other species as well.

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